Quasars and their host galaxies

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Summary. This review attempts to describe developments in the fields of quasar and quasar host galaxies in the past five. In this time period, the Sloan and 2dF quasar surveys have added several tens of thousands of quasars, with Sloan quasars being found to $z > 6$. Obscured, or partially obscured quasars have begun to be found in significant numbers. Black hole mass estimates for quasars, and our confidence in them, have improved significantly, allowing a start on relating quasar properties such as radio jet power to fundamental parameters of the quasar such as black hole mass and accretion rate. Quasar host galaxy studies have allowed us to find and characterize the host galaxies of quasars to $z > 2$. Despite these developments, many questions remain unresolved, in particular the origin of the close relationship between black hole mass and galaxy bulge mass/velocity dispersion seen in local galaxies.

1 Introduction

Quasar astronomy has made some significant advances over the past few years. In this review we will focus on recent developments in the field, and in particular on the links between quasars, their black holes and their host galaxies.

The recent discovery that the mostly dormant black holes in the nuclei of nearby galaxies have masses which correlate with the luminosity and velocity dispersion of their host galaxies has directly linked the quasar phenomenon to galaxy evolution. Black hole mass estimates from host galaxy luminosities can be compared to those which use the results of reverberation mapping and the widths of broad emission lines, with generally consistent results (Laor 1998; Onken et al. 2004). This gives us the possibility of understanding the black hole mass – galaxy mass correlation through a study of the evolution of quasars and their host galaxies.

Reliable black hole mass estimates have also stimulated long-standing debates on how the observational properties of quasars, such as their emission-line spectra, radio-loudness and accretion rates, may (or may not) depend on black hole mass (McLure et al. 1999; Laor 2000; Lacy et al. 2001; Boroson 2002; Woo & Urry 2002). The correlation between black hole mass and the mass of the host galaxy have reinvigorated studies on the links between quasar activity and

galaxy formation. In particular, the relationship between galaxy mergers, starbursts and AGN has come under increased scrutiny using both results from Sloan Digital Sky Survey (SDSS) (Kauffmann et al. 2003) and *Hubble Space Telescope (HST)* studies of quasar host galaxies (McLure et al. 1999; Canalizo & Stockton 2000).

A further recent development, the advent of large, uniform quasar surveys in the optical (the SDSS quasar survey and Two Degree Field (2dF) quasar survey) and the ROSAT X-ray survey, has also helped progress in the subject. One problem that has bedevilled quasar astronomy throughout its history is that selection of quasar samples has been very prone to selection effects. Optical and (soft) X-ray selection techniques are only sensitive to quasars with little dust or gas in the host galaxy to redden or absorb the quasar light. Radio selection is not sensitive to reddening, but only $\sim 10\%$ of quasars are bright radio emitters, and the selection effects associated with radio quasar samples are only just beginning to be understood. In particular, the SDSS is able to pick objects that would be missed from traditional quasar surveys (Fan 1999; Richards et al. 2001), and also objects showing only narrow lines in the optical (Zakamska et al. 2003). Further red quasar selection using 2MASS, 2MASS/FIRST, hard X-ray and now Spitzer surveys is finally revealing the population of dust-shrouded type-2 quasars, whose existence has long been suspected, but of which, until recently, there were few known examples.

Detection of the faint host galaxies of bright quasars has been a long-standing problem in observational extragalactic astronomy. Although the host galaxy and the bright, unresolved quasar nucleus typically have similar total fluxes, the diffuse nature of the galaxy emission can frequently be confused with the extended wings of a poorly-characterized point spread function (PSF). Cosmological surface brightness dimming makes detecting the host galaxies of high redshift quasars particularly challenging. Breakthroughs in quasar host studies came with the advent of the *HST*, with its small, stable PSF, and near-infrared array detectors. Early HST studies with the optical instruments on board allowed the detailed study of nearby quasar hosts (Disney et al. 1995; Bahcall et al. 1997). In parallel, ground-based studies in the near-infrared were able to study the quasars at wavelengths where the flux of the quasar was minimized with respect to the flux of the host galaxy (Dunlop et al. 1993). The marriage of *HST*'s small PSF and the near-infrared NICMOS detector allowed routine discoveries of quasar hosts up to $z \sim 2$ (Ridgway et al. 2001; Kukula et al. 2001).

Adaptive optics are a relatively recent addition to the available techniques for quasar host imaging. Although problematic in some respects (principally PSF variability) AO offers the ability to study larger samples than are practical with the limited observing time available with HST, and, through using 10m-class telescopes, better resolution and surface brightness sensitivity.

We end this review with a discussion of some of the remaining open questions in quasar astronomy, and how advances in telescopes, instrumentation and multiwavelength archives may be able to answer at least some of them in the years to come.

When calculating the intrinsic properties of the quasars we assume a cosmology with $H_0 = 70 \mathrm{kms}^{-1}\mathrm{Mpc}^{-1}$, $\Omega_\Lambda = 0.7$ and $\Omega_\mathrm{M} = 0.3$.

2 New surveys for quasars

Two major new quasar surveys with many tens of thousands of objects have recently appeared. The 2dF quasar survey (Croom et al. 2004a) uses photographic plate material to select UV-excess objects. It is thus a fairly conventional survey, but, by using fibres from a large-scale survey of part of the southern sky conducted by the 2dF multifibre instrument on the Anglo-Australian Telescope it has been able to find many thousands of objects. The SDSS quasar survey uses a multicolour technique to find point-like objects off the stellar locus in colour space (Fan 1999, Richards et al. 2001). It is thus also able to find samples of lightly dust-reddened quasars and very high redshift ($z > 2$) objects which the UV excess technique cannot (Hall et al. 2002; Fan et al. 2004). The SDSS survey is not as deep as the 2dF, but covers a larger sky area with greater photometric accuracy. The Faint Images of the Radio Sky at Twenty-cm (FIRST) radio survey, a large area radio survey to mJy sensitivity, was combined with digitally-scanned photographic plate data to find quasar candidates, selected with a blue colour cut (but one much less severe than optically-selected surveys), to form the FIRST Bright Quasar Survey (FBQS, White et al. 1999). Although the FBQS is much smaller than the SDSS and 2dF surveys, was interesting as it was the first survey able to find significant numbers of quasars with radio fluxes between those of radio-loud and radio-quiet quasars.

The quasar luminosity function has been measured from both the 2dF and the SDSS surveys. Croom et al. (2004a) have analysed the 2dF quasar survey and find that a double power-law with luminosity evolution provides a good fit to the data. Joint use of the 2dF and SDSS databases and techniques is now being applied to further refine estimates of the luminosity function (Richards et al. 2005).

3 Black hole masses and their implications

Perhaps the biggest single advance in the study of quasars in recent years has been our increased confidence in estimates of masses of their black holes. Although a long-term campaign to obtain data for reverberation mapping resulted in estimates of the sizes of broad line regions (BLRs) (and hence, via linewidths and assumptions about cloud dynamics, the masses of the central black holes), it was not until black hole masses could be independently estimated by stellar and gas-dynamical techniques that it became common to use these estimates. Wandel (2002), Peterson et al. (2004) and Onken et al. (2004) showed that black hole masses derived from reverberation mapping and from bulge luminosities of Seyfert-1 galaxies were consistent, and Nelson et al. (2004) showed that black hole masses estimated from the velocity dispersions of Seyfert-1 galaxies were

consistent with the reverberation mapping results. Uncertainties of a factor of a few, e.g. the unknown broad-line region geometry, remain (Krolik 2001). Unfortunately, reverberation mapping studies are restricted to a few tens of (mostly) low luminosity AGN. Thus the relationship between AGN luminosity and BLR radius is not very well established, and its extension to the high luminosities of high redshift quasars uncertain. Reverberation mapping studies use Hβ, whereas studies of high redshift quasars are usually restricted to UV lines which are redshifted into the optical such as MgII and CIV (McLure & Jarvis 2002; Vestergaard 2002). Despite these problems and uncertainties, the ability to obtain even order-of-magnitude black hole mass estimates has allowed some interesting studies to be made.

A further technique for measuring black hole mass was suggested by Nelson (2000), using the width of narrow [OIII] emission line as a proxy for the bulge velocity dispersion. This seems to work well for radio-quiet quasars, but not for radio-louds, where the narrow-line region dynamics are frequently affected by shocks induced by the radio jets. This technique is easy to apply at moderate redshifts, and near-infrared spectra can be used at higher redshifts (Shields et al. 2003). The discovery of significant blueshifts in the [OIII] line relative to systemic velocities (Boroson 2005) has cast doubt on the accuracy of this technique, however.

By combining black hole masses and measured luminosities, we have another key physical parameter, namely accretion rate relative to the Eddington Limit. Studies seem to indicate that the Eddington Rate is indeed a hard upper limit to the accretion rate (e.g. McLure & Dunlop 2004), with a typical optically-selected quasar having an Eddington Ratio (i.e. the ratio of accretion rate relative to the Eddington Limit) ~ 0.1. One important component to this calculation is the bolometric correction factor to convert quasar luminosities in a given waveband to total accretion luminosities. Most studies still use the Elvis et al. (1994) corrections, but new observations of mostly fainter quasars, in particular with the Spitzer Space Telescope in the mid-infrared and the Galaxy Evolution Explorer (GALEX) in the ultraviolet should enable us to significantly improve these corrections and allow luminosity and redshift effects to be fully taken into account.

Estimates for black hole masses have been used to relate observational correlations to physical properties of the AGN. Boroson (2002) showed that the eigenvector 1 of Boroson & Green (1992) is related to the Eddington Ratio. Objects with high accretion rates tend to be at one extreme, with high FeII emission and low [OIII] emission, while those with low accretion rates are at the other end.

4 Radio-loudness of quasars

Another area in which black hole mass estimates have been used to try to improve our physical understanding of AGN is that of quasar radio emission. Amongst well-defined samples of quasars there is a weak, but significant relation between black hole mass and radio-loudness in the sense that the radio-loud quasars have

higher mean black holes masses [Laor (2000), Lacy et al. (2001), Boroson (2002), Jarvis & McLure (2002), Metcalf & Magliochetti (2005)]. Studies of more heterogeneous samples fail to find a correlation of radio-loudness with black hole mass, however (Woo & Urry 2002). When low-luminosity AGN are included amongst the samples being studied, an anti-correlation of radio-loudness with accretion rate relative to the Eddington Limit is seen (Ho 2002), albeit with a lot of scatter. Whether or not the correlation of black hole mass and radio-loudness is real it is surprising that the relationship between radio emission and the physical characteristics of the quasar (accretion rate and black hole mass) is so hard to pin down. Observations of X-ray binary "microquasars" show X-ray emission properties that change significantly during a radio outburst (a hardening of the X-ray spectrum, hypothesized to be due to the temporary formation of an ion-supported torus in the inner part of the accretion disk and a softening during its subsequent collapse, e.g. Fender, Belloni & Gallo 2004), but no obviously analogous behavior is seen in radio-loud quasars. This may be partly a question of timescales of course, but even so one might expect a much bigger difference in the observed properties of radio-loud and radio-quiet quasars were the microquasar analogy to be followed exactly. One promising analogy is between FRI radio galaxies and microquasars in the "low/hard" state with advection-dominated accretion flows, which are able to produce strong outflows (and perhaps radio jets) very efficiently (e.g. Blandford & Begelman 1999). However, directly applying this analogy to high accretion rate radio-loud quasars, which appear to have both highly-efficient relativistic jet production and classic accretion disks, fails.

Black hole spin has long been suspected as being instrumental in radio-loudness. In particular, the Blandford-Znajek mechanism (Blandford & Znajek 1977), in which jets are produced by magnetic fields threading the ergosphere of the black hole requires a rapidly spinning black hole whose rotational kinetic energy is tapped to power the radio jets. X-ray spectroscopy of the relativistic Fe Kα line in Seyfert galaxies can, in principle, be used to measure the radius of the last stable orbit, and hence the spin of the black hole. This is just possible with XMM and Chandra, but to date only one object, MGC-6-30-15, has been studied in sufficient depth to fit the Fe Kα line. Unfortunately, uncertainties in the underlying continuum emission and possible absorption features mean that a definitive statement about whether or not the black hole is spinning is hard to make. Nevertheless, a model with a spinning black hole is preferred by Vaughan & Fabian (2004). Unfortunately for the proponents of the spinning black hole model for the production of radio jets this Seyfert galaxy is radio-quiet.

Closely related to the question of the mechanism for radio-loudness is the question of whether there exists a dichotomy in the radio-loudness parameter (i.e. the ratio of radio to optical/UV luminosity). Early studies of the PG quasar sample suggested this was the case, but more recent surveys have been more ambiguous. For example, the FBQS shows no dichotomy (e.g. Lacy et al. 2001). The case for dichotomy in the much larger SDSS and 2dF quasar samples is probably not made. Although Ivecic et al. (2002) claim that one exists in the SDSS, the claim is based on indirect evidence. A similar analysis by Cirasuolo et al. (2003) based largely on 2dF quasars showed no evidence for a dichotomy.

It is probably fair to say, however, that pending deep, large-area radio surveys, the jury is still out on both whether there is a correlation of radio-loudness with black hole mass and whether there is a dichotomy in the distribution of radio-loudness.

5 Clustering of quasars

One interesting product of the large-scale quasar surveys is an estimate of quasar clustering and its evolution with redshift. Clustering statistics give information on the masses of the dark matter haloes containing the quasars and the value of the bias parameter (the extent to which objects fail to trace the underlying mass distribution). Croom et al. (2005) use the 2dF survey to analyse quasar clustering and its evolution using a sample of over 20000 quasars. They find that quasars occupy dark matter haloes with masses of a few $\times 10^{12} M_\odot$ at all redshifts. An increase in the clustering with redshift is seen, ascribed to an increase in the bias parameter with redshift from close to unity at $z \approx 0$ to about a factor of four at $z \sim 2$. Although quasars at $z \approx 0$ are seen in haloes with the space density of L^* galaxies today, the $\sim 10^{12} M_\odot$ haloes hosting quasars where rarer in the past, and the haloes hosting high-z quasars will grow into group and cluster-sized haloes by the present epoch. Croom et al. interpret this as a trend for lower-mass black holes being more active at low redshift. Of course, in any flux limited survey, the characteristic luminosity of the objects will correlate strongly with redshift, and the possibility of an increase of clustering with luminosity, although not seen in the 2dF dataset, remains a viable alternative explanation. Results from the SDSS, with its higher flux limit, should help to determine whether luminosity or evolution effects are responsible for these results.

6 High-z quasars and reionization

The SDSS has allowed the efficient selection of several $z \sim 6$ quasars. These are important from a cosmological viewpoint for several reasons. The most distant of these show Gunn-Peterson troughs, indicating that at least a small fraction of the intergalactic medium was neutral at $z \approx 6.5$ (Becker et al. 2002; Fan et al. 2003; White et al. 2003). Exactly how much is still the subject of debate, and larger samples of high-z quasars will be needed to establish this (Mesinger, Haiman & Cen 2004). The mere existence of $\sim 10^9 M_\odot$ black holes at $z \sim 6$ is itself interesting, particularly as the detection of FeII emission lines in near-infrared spectra shows that the ISM of the host was already significantly enriched with an element which, at least locally, is mostly produced in type-1 supernovae, with a long ($\sim 0.3 \mathrm{Gyr}$) delay between star formation and the supernova explosions (Freudling et al. 2003; Barth et al. 2003). This implies an early epoch for the first major burst of star formation in the host galaxy ($z \gtrsim 10$). The number density of very high-z quasars can be used to estimate their contribution to reionization. Based on the numbers found so far, it seems that there are not enough of these

objects to reionize the Universe (unless the faint end of the quasar luminosity function is very steep), meaning that star-forming galaxies are the most likely culprits.

7 Broad absorption line quasars

The past few years have seen significant developments in the study of broad-absorption line quasars (BALs), the quasar population which shows absorption by an ionized wind with velocities up to $0.1c$. The number of iron low-ionization BALs (FeLoBALs) known has increased significantly, due principally to new quasar surveys. The FBQS was the first to find significant numbers of these objects (Becker et al. 2000). Subsequently, several FeLoBALs were found in the SDSS survey using colour-based selection criteria (Hall et al. 2002). These remarkable objects have line blanketing by FeII shortward of ~ 2800Å, frequently almost completely extinguishing the UV light from the quasar. They are also significantly reddened by dust, the combination giving them quite different colours than normal quasars.

The discovery of a number of truly radio-loud BALs (including a couple with the classic FRII morphology [Gregg et al. 2000; Brotherton et al. 2002]) has also disproved a long-standing suggestion that radio-loud quasars are incapable of hosting BAL flows. Further radio studies of the FBQS BALs has also undermined the popular orientation model for BALs, in which the BAL winds arise from the surface of the accretion disk, with the line of sight passing through them. This model predicts that BAL quasars are all seen with their accretion disks nearly edge-on. Becker et al. (2000) showed that the radio spectral indices of BALs range from steep to flat, indicating no special orientation for the BAL population.

Modelling of the gas flows causing broad absorption lines has improved significantly, with careful allowance being made for saturation and partial covering effects (e.g. Arav et al. 2001). Attempts to model the very low ionization outflows in the FeLoBAL quasars have raised interesting questions as to whether the low ionization absorbing gas is very far out, at distances of hundreds of parsec (de Kool et al. 2002), or whether the outflow is comprised of a multi-phase gas with dense, low-ionization clouds embedded in a low density, high ionization wind (Everett, Königl & Arav 2002).

8 Finding the obscured quasar population

Recent years have also shown great advances in finding the obscured quasar population. Initially, progress was slow. In the hard X-ray, the small field sizes and depth required to find the obscured quasar population restricted discoveries to a few objects (e.g. Norman et al. 2002, Stern et al. 2002, Padovani et al. 2004). The 2MASS near-infrared survey was able to find some dust-reddened, mostly low-z quasars (Cutri et al. 2002) and by combining 2MASS with the FIRST radio survey, several higher redshift, radio-intermediate reddened quasars were found

(Glikman et al. 2004). However, 2MASS selection was unable to find objects with rest-frame optical reddenings (A_V) greater than a few magnitudes.

Finding the heavily obscured objects, which show no broad lines in the optical and which have rest-frame $A_V \sim 10 - 100$, has proven difficult, and it is only very recently that significant progress has been made. Zakamska et al. (2003) were able to isolate moderate redshift objects with high-ionization narrow lines characteristic of type-2 AGN in the SDSS survey, and later showed that many of these objects show broad lines in polarized light, confiming their quasar nature. A combination of mid-infrared fluxes from the *Infared Space Observatory (ISO)* and 2MASS was able to find objects significantly more reddened than those found by 2MASS alone (Leipski et al. 2004,2005). Using mid-infrared colours from *Spitzer*, Lacy et al. (2004, 2005) also found examples of this type-2 quasar population. A strategy of searching for *Spitzer*-detected radio-intermediate objects has been used successfully by Martinez-Sansigre et al. (2005), who have found several $z > 2$ type-2 quasars. Selection effects for all these techniques still need to be fully understood, but it is clear that the type-2 quasar population is at least comparable in number density to the "normal" quasar population, and perhaps 2-3 times larger. Figure 1 shows the spectra of a type-1 quasar, a lightly-reddened FeLoBAL quasar and a heavily obscured type-2 quasar normalised to approximately the same emission line fluxes.

An upper bound on the total number of quasars, both obscured and unobscured, can be obtained by comparing the mass in black holes in the centers of galaxies today with the total accretion luminosity of the quasar population, divided by the accretion efficiency, a point orignally made by Soltan (1982). The most up-to-date versions of this calculation (e.g. Yu & Tremaine 2002) leave little room for a very large obscured quasar population, but uncertainties about the exact value of the accretion efficiency (i.e. the ratio of the mass-energy accreted onto the black hole to that liberated as accretion luminosity) still allow a significant obscured (or indeed advection-dominated accreting) population. In the standard accretion disk model, accretion efficiency is determined primarily by the radius of the last stable orbit. For a non-spinning (Schwartzschild) black hole this limits the accretion efficiency to ~ 0.1, but the frame-dragging effect of a spinning (Kerr) black hole allows for a closer-in last stable orbit and accretion efficiencies ~ 0.3. Efficiencies of this order are required to accommodate a significant hidden quasar population.

9 Quasar host galaxy studies

Although ground-based studies of quasar hosts have been proceeding for many years, it required the advent of HST to allow robust determinations of the host galaxy properties. Figure 1 shows the regions of the absolute magnitude vs redshift plot covered by the major HST programs. WFPC2 observations of nearby quasars showed that luminous quasars are hosted by massive galaxies, usually early types (Disney et al. 1995; Bahcall et al. 1997; McLure et al. 1999; Dunlop et al. 2003; Floyd et al. 2004). The advent of the NICMOS camera
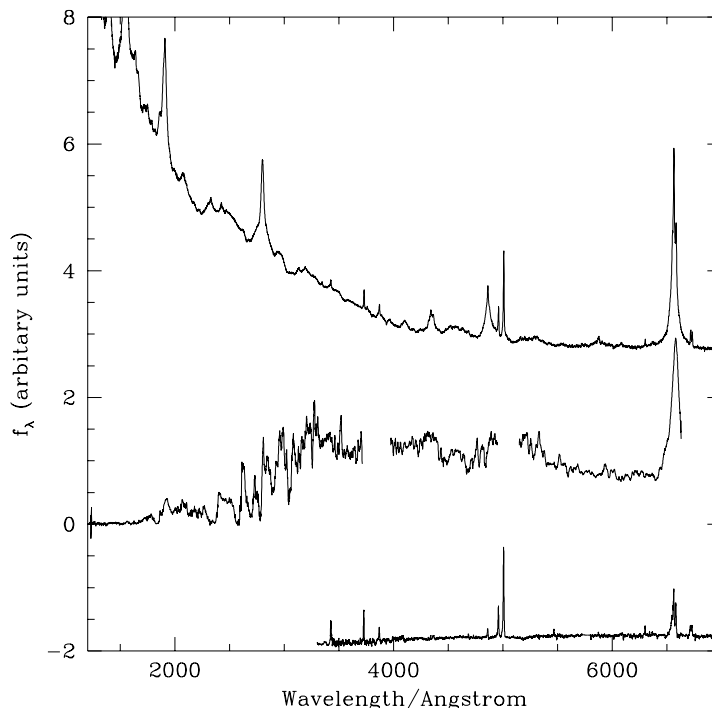
Fig. 1. Rest-frame spectra of traditional and non-traditional quasars: top - composite of normal quasars from the SDSS (Vanden Berk et al. (2001); middle - the $z = 2.65$ FeLoBAL quasar FTM J100424.9+122922 (Lacy et al. 2002a); bottom - a composite of type-2 quasars from Spitzer selection from 3200 - 7000Å (Lacy et al. 2005). The top and bottom spectra have been offset by ± 2 units for clarity. All three spectra have been normalized to approximately the same emission line strength. (The blank regions in the middle spectrum at ≈ 3800 and ≈ 5100Å are zero transparency regions in the near-infrared.)

on HST allowed the study of rest-frame optical emission from host galaxies of quasars at high redshifts for the first time. Kukula et al. (2001) and Ridgway et al. (2001) showed that, at $z \sim 2$, the trend for quasars to be hosted in massive galaxies continues, though less-luminous quasars are generally found in less-luminous hosts (Figure 2). The sample of Ridgway et al. contained quasars of similar luminosity to the low-redshift quasars of Dunlop et al., allowing a direct comparison of the stellar masses of the hosts. This indicated that the stellar masses of the high-z quasars were smaller by a factor of a few than their low-z counterparts. Semi-analytic modelling by Kauffmann & Haehnelt (2000) suggested that the hosts of high-z quasars should be lower in stellar mass, though by a larger factor. Whether this difference is significant or not remains to be established, though the results of Kukula et al. on the hosts of slightly

more luminous quasars are in more disagreement with the predictions of that model. More recent semi-analytic models, which include feedback effects from both supernovae and the AGN, and a different prescription for star formation in massive dark matter haloes at early epochs agree better with observations (e.g. Granato et al. 2003), though a robust, predictive model for galaxy and quasar formation is still lacking. Figure 2 also shows that radio-loud quasars tend to be in more massive hosts (at a given quasar luminosity) than radio-quiets at all redshifts (e.g. Kukula et al. 2001)
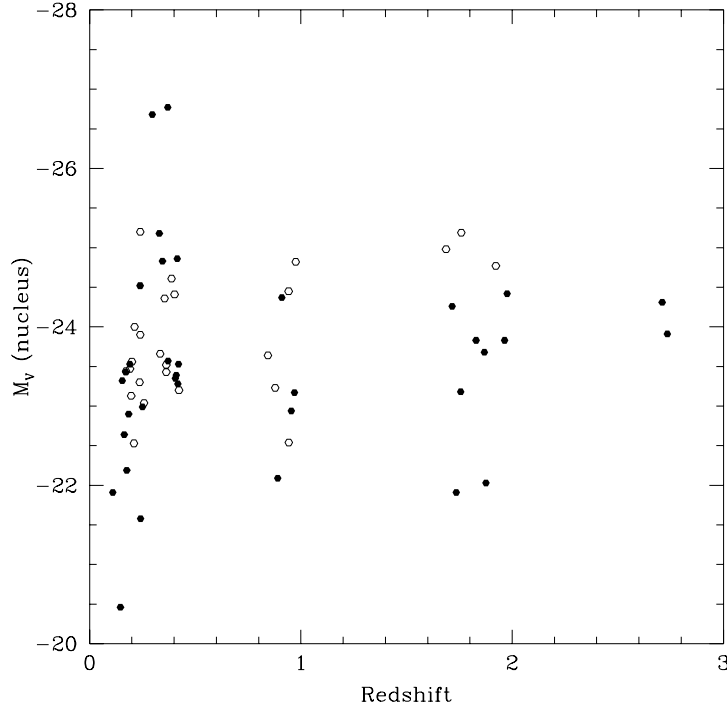

Fig. 2. The absolute-magnitude – redshift plane for quasars studied by the largest HST programs at $z > 0.5$ (Kukula et al. 2001; Ridgway et al. 2001), and the two largest programs at low-z (Dunlop et al. 2003; Floyd et al. 2004). All these samples were imaged close to the rest-frame V-band. Although moderate luminosity quasars are well-represented at most redshifts, there is a lack of high-luminosity quasars, partly for practical reasons of the difficulty of PSF subtraction from quasars whose nuclear light is significantly brighter than that from its host galaxy. Radio-loud quasars are shown as open symbols, radio-quiets as filled symbols.

Spectroscopy of quasar host galaxies has been attempted from the ground. Nolan et al. (2001) found that most quasar host galaxies had evolved stellar populations, ~ 10Gyr old, with only a very small amount of recent star formation.
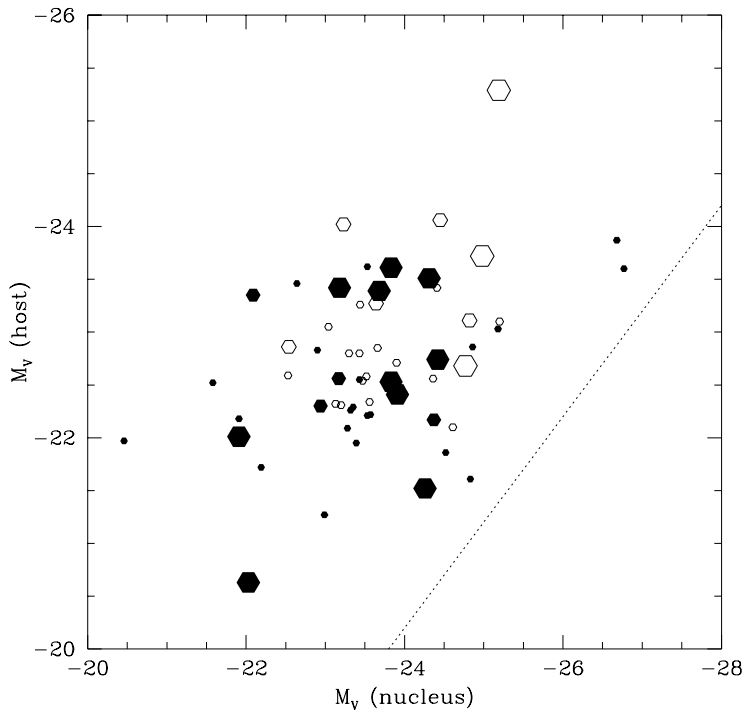
Fig. 3. The samples of Figure 2 with absolute magnitude of the host plotted against nuclear absolute magnitude. Small symbols indicate quasars with $z < 0.5$, medium, those with $0.5 < z < 1.5$, and large, those with $z > 1.5$. The dotted line corresponds approximately to the luminosity expected from Eddington-limited accretion [using the van der Marel (1999) relation]. In general, host and quasar luminosity are correlated, even though few quasars closely approach the Eddington Limit. Note also that there is no strong systematic trend for high-z hosts to be fainter than their low-z counterparts [as predicted, for example, by Kauffmann & Haenelt (2000)], but the dispersion in host galaxy magnitudes does seem to be higher at $z \sim 2$, indicating that a wider range of black hole masses may be involved in quasar activity at early epochs. (It should also be borne in mind that the mass:light ratios of young stellar populations are likely to be lower at high-z, so their black holes may be less massive than their position on this plot would indicate.)

Deeper spectroscopy with Keck by Canalizo & Stockton (2001), however, found evidence of bursts of star formation within the past ~ 100Myr in quasars with far-infrared excesses. Indeed, such populations have also been found in radio galaxies (Tadhunter et al. 2005), and in composite spectra of Seyfert galaxies and low-luminosity quasars from the SDSS (Kauffmann et al. 2003). There is much debate about whether the different results are due to better quality spectra taken closer to the nucleus using 8-10m-class telescopes, or whether there

are real differences in the host galaxy properties of the different quasar samples studied.

In addition to space-based observations, ground-based observations with adaptive optics (AO) are beginning to be exploited for quasar host galaxy studies (e.g., Stockton, Canalizo & Close 1998, Lacy et al. 2002b, Croom et al. 2004b; Falomo et al. 2005). The high spatial resolution of AO is able to concentrate the light of the nucleus, leaving the host much more visible. Although the PSF is not as stable as that produced by space-based observations, the relative cheapness of ground-based telescope time (particularly on smaller telescopes) allows for large surveys not practical with space-based observatories, and on 8m-class telescopes, the resolution exceeds that from HST by a significant factor. Although it is important to bear in mind that surface brightness sensitivity is fundamental to the detection of quasar hosts, AO does significantly improve the ability to detect hosts through concentrating the quasar light into the center of the galaxy image.With laser guide stars becoming available at several major observatories, coupled with large quasar surveys which allow selection of quasars near bright guide stars, this area of research should have a significant impact in the years to come. Host galaxy studies with 8m-class telescopes without adaptive optics, or with only active optics have also been attempted. Although lacking in spatial resolution, the good surface brightness sensitivity of these telescopes has allowed detections of host galaxies out to $z > 4$ (e.g. Falomo et al. 2001; Hutchings 2003).

An early motivation for quasar host galaxy studies was to search for the trigger mechanism of quasar activity (e.g. Stockton & MacKenty 1987). Mergers, or other galaxy interactions have long been thought of as likely triggers as they are able to disrupt stable gas which might fall onto the black hole. What has never been clear, however, is how disturbances due to mergers or interactions on kpc scales influence the gas motions within the sub-pc inner region of the AGN. Indeed, McLure et al. (1999) conclude that few of their quasar hosts show obvious signs of interaction. However, the presence of moderate age stellar populations in quasar hosts suggests there may be a delay between the large-scale disruption (which would trigger a starburst almost instantaneously) and the onset of quasar activity. One possibility is that dust-reddened and/or type-2 quasars may represent an early stage in quasar evolution. Canalizo & Stockton (2001) find that several of their IR-excess quasars are low-ionization BALs with significant dust reddening, and, although many type-2 quasars have classic high-ionization emission lines in their optical spectra, there are several whose spectra either lack emission lines, or contain only emission lines from starbursts (e.g. the "type-3" quasars of Leipski et al. 2005). These might represent quasars in a very early, completely dust-shrouded phase in their evolution where even the narrow-line region is obscured. On the other hand, an HST-based study of the host galaxies of 2MASS-selected dust-reddened QSOs by Marble et al. (2003) found no significant difference between the hosts of dust-reddened and normal QSOs in terms of the spread in galaxy type and evidence of recent merger activity.

10 Open questions

Over the past few years quasar astronomy has undergone something of a revolution. From surveys of a few hundred quasars we have gone to surveys of several tens of thousands. We have much more confidence in our ability to estimate the important physical parameters of quasars, namely black hole mass and accretion rate. The highest redshift quasar is now at $z > 6$. We have resolved the host galaxies of quasars out to $z > 2$. We are close to being able to place much-improved constaints on the numbers of dust-hidden quasars, which studies suggest at least equal, and perhaps exceed, the numbers of "classical" blue quasars. Although finding the most heavily obscured objects will always be hard, nature seems to be helping us by providing many of these objects with the "obscuring torus" geometry which makes them much more visible in the mid-infrared. Nevertheless, we still have open a number of important questions - indeed, our new information has allowed us to ask new ones. Perhaps the most fundamental is the nature and evolution of the black hole mass – bulge mass relation, as it demonstrates a clear link between quasars and their host galaxies. This link might be established by a mechanism in which the quasar acts as a govenor providing negative feedback to star-forming processes in the host galaxy (e.g. Silk & Rees 1998).

Other questions remain. Why does the evolution of quasars so closely resemble pure luminosity evolution, even though we know high redshift and low redshift quasars must be very different phenomena, one fundamentally linked to galaxy formation and growth, and the other apparently a rare phenomenon which seems to at best reflect the end results of a merger several hundreds of Myr earlier? How are outflow phenomena such as radio-loud quasars and BALs linked to the normal quasar population? Is the obscured quasar population linked to the normal quasar population through evolution, orientation, or both? Exactly how many quasars are hidden by dust?

Future techniques to study quasars will probably involve a shift from the study of pre-selected quasar samples towards survey-based samples. Data mining of public multiwavelength surveys will result in the discovery of objects which occupy unusual parts of parameter space, such as high redshift type-2 quasars (Padovani et al. 2004). New radio telescopes such as the Low Frequency Array (LOFAR) and the Square Kilometer Array, which can image deep enough over a large enough area to measure the radio-luminosity function of radio-quiet quasars will shed new light on the relationship of radio jet power to other quasar properties. With robotic telescopes becoming more common, it becomes feasible to undertake reverberation mapping studies of larger samples of objects for longer periods, including higher luminosity AGN and quasars, which can be used to improve black hole mass estimates. Statistical studies of quasar variability (e.g. Vanden Berk 2004; de Vries et al. 2005) will become easier and more accurate with e.g. the Large Synoptic Survey Telescope, and should open up new ways of investigating the quasar phenomenon.

With the future of HST uncertain, adaptive optics is certain to become a more important tool for the study of quasar host galaxies. Future space missions

such as the James Webb Space Telescope and the Terrestrial Planet Finder (Cononograph) will play an important role, but both missions are some years away. Of the open questions, probably only the nature and numbers of the obscured quasar population is one we will be able to answer soon. The others will require further observations and theoretical modelling before we will be able to make progress.

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